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Introduction

Endodontically treated teeth are generally associated with a shorter survival compared to vital teeth, by far the most prevalent cause of extraction of root canal treated teeth is unrestorable decay (Fuss *et al.* 1999, Chen *et al.* 2008, Zadik *et al.* 2008). While recommendations based on clinical experience have been suggested, there is little evidence on the impact of remaining coronal tooth structure on the survival of endodontically retreated teeth.

There have been several suggestions on how to classify the amount of remaining sound coronal tooth structure in endodontically treated teeth. Some authors refer to the percentage of residual tooth structure without defining how this percentage has been measured (Juloski *et al.* 2014, Aurelio *et al.* 2015), while others use more generic terms such as ‘substantial’ or ‘minimal dentine height’ remaining (Creugers *et al.* 2005, Fokkinga *et al.* 2007), limited loss of coronal tooth structure in teeth with mesial or distal loss decay with cusp preservation (Mannocci *et al.* 2002).

In vivo studies have associated the medium- to long-term survival of endodontically treated teeth and their restorations with the number of remaining cavity walls, presence of a ferrule (Ferrari *et al.* 2012, Naumann *et al.* 2012, Sterzenbach *et al.* 2012) and height of coronal dentine remaining (Fokkinga *et al.* 2007) prior to core build up and crown preparation. None of these methods quantifies in a reproducible fashion the amount of residual tooth structure.

The outcome of root canal treatment also depends, amongst many other factors, on adequate coronal restorations (Ray & Trope 1995, Kirkevang *et al.* 2000, Tronstad *et al.* 2000). In the long-term, an inadequate coronal restoration may be a source of micro-leakage, and ultimately failure of the endodontic treatment (Saunders & Saunders 1994, Siqueira *et al.* 1999).

Recent development in digital dentistry allows high-resolution 3-dimensional (3D) virtual models of the patient’s dentition and soft tissues to be directly captured. Digital impressions are becoming increasingly common in dentistry (Seelbach *et al.* 2013, Lin *et al.* 2015, Martin *et al.* 2015). The accuracy of linear measurements on digital models obtained from intraoral scanner has been demonstrated in a recent study (Wiranto *et al.* 2013).

Cone beam computed tomography (CBCT) is a relatively new radiographic method, which overcomes the limitations of 2D radiographs (Patel *et al.* 2010, Patel *et al.* 2015). A recent *ex vivo* human cadaver study which used histology as the reference standard confirmed that CBCT was more accurate than central view and parallax view digital periapical radiographs at detecting apical periodontitis (Kanagasingam *et al.* 2016).

The aim of this study was to evaluate the endodontic outcome of retreated posterior teeth in relation to the volume of residual coronal tooth structure measured with an intraoral scanner.

Material and methods

Patient selection

Subjects included in this study were patients referred to an endodontic postgraduate unit, XXXX for management of failed initial endodontic treatment. Patients with at least one posterior (premolar and molar) root treated tooth diagnosed with endodontic post-treatment disease were included in this study. Only teeth in occlusal function with a natural opposing tooth were included in this study. Patients were excluded if they were pregnant, immunosuppressed, having non-restorable teeth or teeth with periodontal probing depth >3mm. The clinical study was approved by the XXXX Research Committee (reference no. 13/LO/1171). In total, 204 posterior teeth from 182 patients were initially included in this study, however, upon dismantling the tooth, 48 teeth were found to be not restorable and were therefore excluded.

Clinical and radiographic evaluation

All teeth were assessed clinically and radiographically at baseline (T0), and at recall (T12). The data was anonymised and transferred into electronic data-sheets (Microsoft Excel 2011, Microsoft, Richmond, Washington, USA).

Periapical radiographs and CBCT scans were taken pre- and 1-year post-operatively. Pre-operative periapical radiographs using the paralleling technique were obtained with digital phosphor plate system (Digora® Optime, Soredex, Tuusula, Finland) using a beam positioning film holder (Dentsply Rinn, Elgin, Illinois, USA). All radiographs were exposed using a dental X-ray machine (Heliodent, Sirona, Bensheim, Germany) operating at 65kV, 7mA and an exposure time of 0.16-0.25 seconds. A small volume CBCT scanner (3D Accuitomo 80, J. Morita, Kyoto, Japan) with a 4X4cm field of view (FOV), 0.125mm of voxel size, 90kV, 4mA, and 17.5 seconds was used to obtain CBCT images. All CBCT data were reconstructed using the system’s proprietary software (i-Dixel® 3DX, J. Morita) with 0.16mm slice intervals and 1.2mm slice thickness.

Clinical intervention

The restorability of the tooth was confirmed by an experienced restorative dentist. Root canal retreatments and subsequent restoration with a cuspal coverage restoration was carried out by Endodontic postgraduate students supervised by qualified endodontic staff. Prior to the initiation of the study, the operators were trained and calibrated to follow a standardised treatment protocol.

Root canal retreatment was carried out in two treatment sessions under local anaesthesia and rubber dam isolation as described in a previous paper (Davies *et al.* 2016). The operators used dental operating microscopes (3 step entrée Dental Microscope, Global, St. Louis, Missouri, USA) during all procedures. In brief, the existing restoration(s) was removed, coronal gutta-percha and enlargement the coronal one-third of the canal was achieved by using Gates-Glidden drills (Dentsply Maillefer, Ballaigues, Switzerland) sizes 2 or 3. Hedström files and K-flexofiles® (Dentsply Maillefer) were used to remove the existing gutta-percha from the middle and apical third of the canal, respectively. A hand instrument K-flexofile (Dentsply Maillefer) size 6 to size 10 was used to negotiate each canal until full working length was determined and confirmed by both electronic apex locator (Root ZX®, J. Morita) and digital periapical radiograph. Re-instrumentation was performed in a crown-down manner using ProTaper® Universal rotary instruments (Dentsply Maillefer) to the full working length, using size S1 to a minimum of F2. The canals were frequently irrigated with a copious amount of 1% sodium hypochlorite (Adams Healthcare, Leeds, UK) delivered using a syringe and a 27-guage needle at each file change. A penultimate irrigation with 17% EDTA (Ethylene Diamine Tetraacetic Acid, Pulpdent, Watertown, Massachusetts, USA) was performed followed by final irrigation with 1% sodium hypochlorite. All canals were filled with gutta-percha (Dentsply Maillefer) and Pulp Canal Sealer (Kerr-Sybron, Romulus, Michigan, USA) using a warm vertical condensation technique.

Upon completion of root canal retreatment, the canal orifices were sealed with a thin layer of either flowable composite resin (X-Flow, Dentsply Maillefer) or conventional GIC cement (Fuji IX, GC Corporation). Subsequently, all enamel and dentine surfaces of the cavities were etched and bonded using a two step etch and rinse bonding agent (Scotchbond Universal System, 3M ESPE) as per manufacturer's instructions. Finally, the tooth was restored incrementally with composite resin (Ceram X Duo, Dentsply Maillefer) restoration. All teeth were restored with a cuspal coverage restoration within 1 month. Only one maxillary and one mandibular premolar teeth required a fibre-post retained core.

Volume measurements

Once root canal retreatment had been completed and prior to core placement, a single- phase consistency impression (impression a) was taken using polyvinylsiloxane impression material (Aquasil Monophase, Dentsply Caulk, Milford, Delamere, USA) in a sectional impression tray. A second sectional impression (impression b) was taken after the tooth had been restored with a crown (Figure 1).

The impressions were poured using Moonstone™ (Bracon, Etchingham, England) dental stone. All casts were digitised using a 3M™ True Definition scanner (3M ESPE) to generate 3D datasets. These 3D datasets were imported into surface metrology software (Geomagic® Control™ 2014.3, 3D Systems Inc., North Carolina, USA) for superimposition of datasets. For superimposing the 3D datasets, 25,000 common points were used. Once the superimposition was performed, the coronal tooth structure was isolated from the surrounding gingiva and adjacent teeth by using Geomagic software. The differences in the volume of remaining coronal tooth structure between these two datasets were computed in order to obtain the percentage of remaining coronal tooth structure.

Residual cavity walls

For teeth presenting with no pre-treatment crowns, all cavity walls, which exceeded a minimum height of 3mm, a thickness of 1mm, and extended at least 3mm in length, were included. The height of the walls was measured from the gingival margin to the tip of the residual dentine wall in a vertical direction, and the thickness of the walls was measured from the inner to the outer surface of the residual dentine wall in a horizontal direction. The length, height and thickness of all walls were measured using measurement tools in Geomagic Control software (Figure 2). All teeth retained at least 1 coronal wall.

Follow-up assessment

Patients were contacted 1 month in advance of the 12-month (T12) follow-up appointment to confirm their attendance. A clinical and radiographic assessment was carried out, this including parallel periapical radiographs and CBCT scans with the same exposure settings for the pre-operative scans.

Quality of coronal restoration assessment

The quality of coronal restoration at 1-year was assessed clinically and radiographically. Two experienced, trained and calibrated examiners assessed the clinical and radiographic quality of restorations according to criteria modified from those described by Craveiro *et al.* (2015). Clinically, coronal restoration quality was considered to be ‘adequate’ when it showed good marginal fit with no recurrent caries or when, despite superficial ceramic fractures, the tooth was still intact, while restorations with a detectable evidence of any marginal discrepancy, overhangs, open contact with recurrent caries, or debonded restoration were considered as ‘inadequate’.

For radiographic evaluation, all periapical radiographs were displayed on a PowerPoint (Microsoft PowerPoint 2011, Microsoft) presentation and evaluated by two examiners jointly. Any restoration was judged as ‘adequate’ if it appeared intact on periapical radiographs and considered as ‘inadequate’ if there were radiographic signs of restoration with open margins, overhangs, or recurrent caries. After follow-up, all inadequate restorations were replaced.

Radiographic assessment of the endodontic outcome

For each tooth, an endodontist, who was not part of the radiological assessment and experienced in using CBCT in endodontic therapy was responsible for identifying the relevant sagittal, coronal, and axial slices that best confirmed the presence/absence of periapical radiolucency or showed the largest periapical radiolucency. The apical-third of each root was vertically aligned using Accuitomo software (One Volume Viewer®, J. Morita). All identifying patient information was removed. The radiographs at T0 and T12 were displayed together as PowerPoint (Microsoft) presentations using two 13-inch laptop computers (MacBook Pro, Apple, California, USA) with a resolution of 1680 x 1050 pixel to allow the examiners to determine the healing status of each root. A similar approach was followed when the CBCT images were assessed. All slides in the presentations were randomly ordered and each slide included 1 periapical radiograph or 3 CBCT spatial planes (sagittal, coronal and axial) for each root of the tooth under examination (Figure 3). The raw CBCT data were also accessible for the examiners whenever additional information was needed, the examiners were allowed to measure the maximum diameter of the periapical lesion when they thought this was appropriate. The radiographic interpretation was conducted in a quiet, dimly lit room.

A consensus panel of two pre-calibrated experienced endodontists were asked to identify the presence/absence or change (increase/decrease) in the size of an existing periapical radiolucency associated with the apical portion of the roots. The examiners were not involved in carrying out the endodontic treatment. For calibration, the examiners were asked to assess the healing status in 50 examples of 1-year follow-up periapical radiographs and CBCT images of endodontically treated teeth that did not belong to the present experimental material. Furthermore, each examiner was asked individually to assess 50 pairs of the periapical radiographs and CBCT images a second time after 4 weeks in order to determine the inter-examiner reliability.

The assessment of radiographic images was performed in 2 viewing sessions, with at least a 1-week interval in between. During each session, the consensus panel was asked to assess 50% of the periapical radiographs (n=68/137) and 50% of CBCT scans (n=160/320). The consensus panel reliability was determined by jointly re-assessing 100 pairs of the pre-operative and 1-year post-operative radiographic images following a 2-week interval.

In multi-rooted teeth, the presence/absence of periapical radiolucency on each identifiable root was reported. This allowed a direct comparison of like-pairs of specific roots using radiographs and CBCT images as described by Patel *et al.* (2012b). The outcome of the tooth was assessed according to the root that had the worst treatment outcome.

A periapical lesion was diagnosed as a periapical radiolucency which was at least twice the width of the periodontal ligament space (Low *et al.* 2008, Bornstein *et al.* 2011). Based on the radiographic changes between T0 and T12 images each root was allocated to an outcome category (Table 1). In the present study, teeth with healed lesion (outcome 5), healing lesion (outcome 4) or unchanged healthy periapex (outcome 6) were considered to have a 'favourable outcome', whereas teeth that developed a new lesion (outcome 1), teeth which showed an increase in the size of existing lesion (outcome 2), no change in the existing lesion size (outcome 3), and teeth with symptoms and/or clinical signs of failure (i.e. tenderness to percussion and/or palpation, presence of swelling and sinus tract), irrespective of the radiographic outcome were considered to have an 'unfavourable outcome'.

Post-operative root filling length was assessed on periapical radiographs and dichotomised as 'adequate' (0–2 mm short of the radiographic apex) and 'inadequate' [short (>2mm short of the radiographic apex) or long].

Statistical analysis

Data analysis was carried out using IBM SPSS software (version 23, IBM, NY, USA). Fleiss's kappa coefficient was used to assess the intra-consensus panel agreement and inter-examiner agreement for radiographic assessments of periapical health, also to evaluate the intra-consensus panel agreement for restorations quality. A Cohen kappa correlation was calculated to determine the correlation between clinical and radiographic assessments of the quality of coronal restorations. The outcome of root canal retreatment was dichotomised into 'favourable' versus 'unfavourable', whereas the apical extension of the root filling and the quality of coronal restoration were dichotomised into 'adequate' versus 'inadequate'.

In order to determine the association between the volume of remaining coronal tooth structure and the outcome of root canal retreatment, the raw volume was analysed by means of receiver operating characteristic (ROC) curve and Youden index (sensitivity+ specificity-1) to identify the optimal cut-off point for volume dichotomisation.

Chi-square tests were used to determine the association between the outcome and the other variables (volume of remaining tooth structure, the number of dentine walls remaining, the apical extension of root canal filling and the quality of coronal restoration). If the chi-square test showed that any of these variable was significant, then the joint association of these variables with the treatment outcome was tested using a logistic regression model. The significance level was set at α=0.05.

A McNemar's test was used to determine if there were any significant differences in favourable and unfavourable outcomes of treatment when assessed by periapical radiographs and CBCT. Fisher's Exact test was used to determine whether there was any significant association between the pre-operative periapical status and the outcome of the treatment.

Results

One hundred and fifty-six teeth (140 patients) were root canal retreated (Figure). Nineteen (13.6%) patients dropped out of the trial. Of those patients, 10 were not able to attend the review appointment, but they confirmed that the tooth was asymptomatic and in function. Reasons for drop out are described in Table 2.

At the 1-year review, 137 (121 patients) of the original 156 teeth were available for evaluation. The recall rate was 87.8% for the teeth, and 86.4% for the patients. Among 137 teeth, 5 teeth (4 molars, 1 premolar) in 5 patients experienced complications [apical perforation (1), root resorption (1), ledged (2) and blocked canals (1)] and did not reach the endpoint of follow-up as further treatment was required. These patients had persistent clinical symptoms prior to and post-retreatment. These 5 teeth underwent periapical microsurgery and they were asymptomatic 1-year post-surgery. This group of teeth was included in the analysis of the outcome of root canal retreatment as clinical failures and excluded from the analysis of the quality of coronal restorations assessment.

The average age was 43 years; 84 patients were female (69.4%) and 37 male (30.6%). The frequency distribution of teeth is shown in Figure 5. There was no significant difference between the treatment outcomes in maxillary versus mandibular teeth (*P*= 0.484).

Based on Youden index associated with ROC curve, the optimal cut-off point of remaining tooth volume was 29.5%. Accordingly, the remaining coronal volume of teeth was dichotomised into less than 30% (n=33), and more than 30% (n=104). The percentages of unfavourable outcomes associated with teeth presented with different volumes (<30%, >30%) of remaining coronal tooth structure are shown in Figure 6. Chi-square test showed that the volume of remaining coronal tooth structure (<30%, >30%) was a significant predictor of endodontic failure as demonstrated by CBCT with teeth with less than 30% remaining coronal tooth structure showing a significantly higher number of unfavourable outcomes (χ^2=4.235, OR=2.58; 95% CI: 1.026, 6.487, *P*=0.040).

At T12 recall assessment, radiographs showed that the healing (outcome 4) and healed rates (outcomes 5 & 6) were 18.2% (24 teeth) and 74.3% (98 teeth), respectively. With CBCT scanning, the healed and healing rates were 34.1% (45 teeth) and 50.8% (67 teeth), respectively (Table 3).

The overall percentage of favourable results was 88.3% using periapical radiographs, and 81.8% using CBCT (Table 4). There was a significant difference in the favourable and unfavourable outcomes of teeth when assessed by periapical radiography and CBCT (*P*=0.035).

There was one tooth that demonstrated complete healing with a radiograph but had a tenderness to percussion and palpation with periapical radiolucency present on CBCT, therefore its outcome was classified as unfavourable. Of the 25 teeth classified as having unfavourable outcome with CBCT, 11 teeth had signs and symptoms. All patients that presented with symptoms and/or signs had radiographic evidence of apical radiolucency detected by CBCT.

The percentage of teeth with healthy pre-operative periapical status was 36.5% (50 teeth) when assessed by periapical radiography, and 13.9% (19 teeth) when assessed by CBCT. CBCT revealed that the favourable outcome for teeth without pre-operative periapical radiolucencies (100%) was significantly higher than teeth with pre-operative radiolucencies (78.8%) (*P*=0.024).

Pre-operative perforations were detected in 12 teeth, of which 11 had favourable outcomes. Eleven teeth were treated with mineral trioxide aggregate (MTA) and 1 tooth with intermediate restorative material (IRM).

The apical extension of root filling had no significant impact on the periapical health (χ^2=0.300, OR=0.756; 95% CI: 0.277, 2.063; *P*=0.584). Six out of the 25 teeth with unfavourable outcome presented with inadequate (short or overfilled) root filling length. Of the 112 teeth with favourable outcome, 33 (30%) had not been filled to an adequate length (short [19%] or overfilled [11%]). Eight of the 33 teeth with <30% volume of remaining coronal tooth structure had inadequate root filling length, of which 1 tooth had unfavourable outcome and 7 teeth had favourable outcome.

The intra-consensus panel agreement and the inter-examiner agreement for assessing the treatment outcome and the quality of coronal restorations ranged between 0.71 and 0.76 (Table 5).

Eighty-nine teeth (67 molars, 22 premolars) with no pre-operative full cuspal coverage were included in the analysis to assess the influence of the number of remaining dentine walls on the outcome of root canal retreatment. Because of the very small sample size (3 teeth) in 1-wall group, these teeth were added to the 2-wall group for statistical analysis considerations. The chi-square test showed no significant association between the number of coronal walls remaining and the outcome of the treatment (χ^2=0.719, OR=2.44; 95% CI: 0.291, 20.517, *P*=0.698). Frequencies and percentages of the unfavourable treatment outcomes among the four tested groups are reported in Table 6.

A total of 132 teeth (116 patients) were assessed clinically and radiographically. The clinical evaluation of the quality of coronal restoration identified 6 (4.5%) restorations with marginal discrepancy; these restorations were replaced. No caries, decementation or root fractures were recorded. Radiographically, 7 (5.3%) of the coronal restorations were unacceptable, including six restorations with open margins and 1 restoration with overhang margins. Comparing clinical to radiographic scoring, the percentage of agreement was 91.7% and the Kappa score was 0.11. When the clinical and radiographic evaluations were combined, unfavourable treatment outcomes were detected in 15% of teeth with acceptable restorations and 16.7% of teeth with unacceptable restorations. No correlations were observed between treatment outcome and restoration quality (χ^2=0.024, OR=1.133; 95% CI: 0.229-5.606; *P*=0.878). Table 7 shows data on the quality of coronal restoration and its relation to the outcome of root canal retreatment.

Discussion

The most significant finding of this study was that root canal retreated teeth with <30% volume of sound remaining coronal tooth structure showed a significantly higher failure rate than teeth with a residual tooth structure volume >30%. Teeth with less than 30% of their original tooth volume had a 2.58-fold (95% CI: 1.026, 6.487) greater chance of unfavourable treatment outcome than those that had more than 30% volume at the 1-year follow-up period. These results were independent of the pre-operative presence of procedural mistakes. A combination of variables, such as undetected tooth cracks, difficulty to achieve ideal isolation, increased exposure time to oral bacteria, and the difficulty in achieving a perfect coronal seal may affect more severely the outcome of root canal retreatment of teeth with increased loss of tooth structure. To our knowledge this is the first clinical study investigating this particular aspect of root canal retreatment.

Patients were reviewed 1 year post-treatment as per ESE guidelines (European Society of Endodontology 2006). Several studies have shown that healing of apical periodontitis occurred in most cases during the first year (Huumonen & Ørstavik 2013, Zhang *et al.* 2015, Azim *et al.* 2016). The recall rate in the current study was 87.8% for teeth and 86.4% for patients.

The examiners were experienced in interpreting CBCT data and were calibrated to obtain a consistent and reliable assessment of the treatment outcome. Viewing sessions were kept as short as possible to minimise the chance of examiner fatigue. The use of a consensus panel was in accordance with several previous studies to minimise inter-examiner variation (Patel *et al.* 2012b, Hashem *et al.* 2015, Davies *et al.* 2016). A good level of consensus panel agreement and inter-examiner agreement (0.71-

0.76) was found for periapical radiographs and CBCT assessment of treatment outcome, and for radiographic assessment of coronal restoration quality. The examiners were blinded to the volume of remaining tooth structure corresponding to the teeth assessed.

Before commencing any treatment, an accurate assessment of the remaining coronal tooth structure and prognosis evaluation are important to make a good treatment plan. Tzimpoulas *et al.* (2012) reported that a significant loss of dentine was the main reason for the extraction of endodontically treated teeth referred to endodontists. Tang *et al.* (2010) concluded that although the causes of potential tooth fracture are multifactorial, the loss of tooth structure and the stresses generated during endodontic and restorative procedures were possible causes of post-endodontic tooth fractures (Tang *et al.* 2010).

There is evidence to suggest a direct correlation between the remaining coronal tooth structure and the survival of root canal treated teeth and long-term success of the restorations (Nagasiri & Chitmongkolsuk 2005, Cagidiaco *et al.* 2007, Ferrari *et al.* 2012). In these studies, the qualitative means used to estimate the amount of remaining tooth structure may have led to overestimation or underestimation of the amount of dentine that actually remained at the coronal level. Moreover, many of these studies (Monticelli *et al.* 2003, Cagidiaco *et al.* 2007, Ferrari *et al.* 2012) were limited to assess endodontically treated premolars with and without posts and thus the findings may not be applicable to molar teeth.

Murphy *et al.* (2009) attempted to assess both the thickness to height ratio and volume of remaining coronal tooth structure using a laser profilometer scanner and a tooth restorability index (TRI). In this study, the authors blocked the dentine walls undercuts with a siloxane impression material to overcome the inability of a laser profilometer to scan these undercuts (Murphy *et al.* 2009). This measurement method is therefore inaccurate, and its ability to predict tooth survival or endodontic outcome has not been proven in a clinical trial.

Currently, there is no standardised method to quantify the amount of remaining coronal tooth structure. In the present study, the intraoral digital scanning provides reliable and accurate measurement of tooth volume (Al-Nuaimi *et al.*submitted).

Several previously published clinical studies (Ferrari *et al.* 2007, Cagidiaco *et al.* 2008, Ng *et al.* 2011, Ferrari *et al.* 2012) have examined the influence of post placement and residual coronal dentine (i.e. number of dentine walls remained) on the survival of endodontically treated premolars. However, root canal treatments and restorations of premolars represent a small proportion of restorations of root canal treated teeth, and an even smaller proportion of root canal retreated teeth.

The present study was not statistically powered to assess the effect of the number of remaining walls on the outcome of root canal retreatments, however, in the 2- and 3- and 4-walls groups, the percentage of unfavourable outcomes was 18.2%, 17.9%, and 8.3% respectively. Teeth with 2 and 3 walls remaining had a 2.44-fold (95% CI: 0.291, 20.517) greater chance of unfavourable outcome than teeth with 4 walls remaining, however, this difference did not reach statistical significance (*P*=0.698). A similar but statistically significant trend was revealed in previous studies assessing the outcome of restorations of endodontically treated premolars restored with and without fibre posts (Ferrari *et al.* 2007, Cagidiaco *et al.* 2008, Ferrari *et al.* 2012).

The use of CBCT for the detection of apical radiolucencies has been recently validated in histological cadaver studies (Kanagasingam *et al.* 2016). CBCT has been successfully used recently for healing assessment after root canal treatment, retreatment and indirect pulp capping procedures (Patel *et al.* 2012b, Hashem *et al.* 2015, Davies *et al.* 2016). Irrespective of the clinical signs and symptoms, CBCT imaging revealed lower healing outcome rates (84.9%) for root canal retreatment compared with periapical radiographs (92.5%) when the outcome was assessed at T12 follow-up (*P*=0.021).

The favourable outcome observed in the present clinical trial, as assessed by periapical radiographs, concurs with the findings of previous studies (Imura *et al.* 2007, Ng *et al.* 2011), which also reported a success rate (loose criteria) for root canal retreatments comparable to the 88.3% value recorded in this research. Of the 98 cases that appeared to have no periapical radiolucency on periapical radiographs at T12 recall, 10 appeared as enlarged or maintained the same lesion size when imaged using CBCT. The favourable outcome percentages recorded in this study are in similar to a previous prospective retreatment study (Davies *et al.* 2016) where favourable periapical radiographs and CBCT percentages were 93% and 77%, respectively. In contrast, in a study by Metska *et al.* (2013), the percentage of retreated teeth with reduced volume of periapical radiolucencies assessed by CBCT was 57% (Metska *et al.* 2013), which was lower than the finding of our study. However, in Metska's study the sample size was limited to 35 teeth, and using the volumetric changes in periapical lesion size instead of the visual interpretation of the images could explain the low percentage of healed cases 1 year after retreatment.

In the present study, CBCT detected 22.6% more pre-operative periapical radiolucencies than periapical radiographs. This finding has been documented in several previous clinical studies (Estrela *et al.* 2008, Patel *et al.* 2012a, Weissman *et al.* 2015). The results of this study showed a significant association between the pre-operative apical status and the treatment outcome (P=0.024). This is in agreement with other studies (Imura *et al.* 2007, Ng *et al.* 2011, Azim *et al.* 2016).

In the current study, over-filling or under-filling of the root canal had limited impact on periapical health even with the presence of pre-operative periapical radiolucencies (OR=0.756; 95% CI: 0.277, 2.063; P=0.585). These results agree with the findings of previous studies (Sjögren *et al.* 1990, Lin *et al.* 1992) but contradicted other studies (de Chevigny *et al.* 2008, Ng *et al.* 2011, Azim *et al.* 2016).

In the present study, the only inadequate coronal restorations observed were due to the presence of open margins or overhang restorations. No debonding was recorded. The presence of large marginal discrepancies can expose the luting material to the oral environment (Jacobs & Windeler 1991). Recontamination of the root canal system by coronal leakage has been emphasised (Siqueira *et al.* 1999, Siqueira 2001). Ray and Trope (1995) found in a retrospective study that the quality of coronal restorations, scored only on radiographs, had a higher significant impact on the periapical health than the quality of root canal filling (Ray & Trope 1995). However, no information was available regarding the pre-operative diagnosis of the teeth, and the time elapsed between root canal completion and placement of the coronal restoration. In the present study, the unfavourable outcome in teeth assessed both clinically and radiographically as having adequate restoration was 15%, compared to

16.7% in endodontically treated teeth with inadequate restorations. Based on these data, the interaction between the quality of coronal restoration assessed clinically and radiographically, and the outcome of root canal retreatment was not statistically significant (P=0.878), however this study was not statistically powered to demonstrate such differences.

Postgraduate students under supervision of experienced educators in endodontics carried out all the endodontic treatments and definitive coronal restorations in this study, Anterior teeth were not included in this study. All coronal restorations were metal-ceramic crowns, this allowed the exclusion of variables such as different tooth types, different operator skills and different restoration types which had the potential to affect the outcome of the root canal treatments

Further investigation, along with a longer observation period (3 years), is currently on going to assess the survival of the teeth included in the present study

Conclusions

At 1-year follow-up, the percentage of unfavourable outcomes of root canal retreated teeth was significantly higher when less than 30% of the original tooth tissue structure was present at baseline.

The results of this research may enable the clinicians to develop methods of measuring the volume of residual tooth structure using intraoral scanners and to predict the endodontic outcome and potentially the survival probability of endodontically treated teeth.

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Figure legends

Figure 1 Representative (a,b) stone casts, 3D digital models of (c,d) stone casts, and (e-f) tooth 46 prior to core placement and after crown placement.

Figure 2 Examples of three-dimensional digital model representations of the remaining coronal dentine walls following the completion of root canal retreatment (a) only one wall remained, (b) two walls remained, (c) three walls remained, and (d) four walls present.

Figure 3 (a,b) Pre- and 1-year post-operative periapical radiographs of the 36 where both examiners confirmed complete healing of the periapical lesions associated with the mesial (yellow arrow) and distal roots (red arrow). (c-d) Pre- and post-operative CBCT images of the same tooth reveal complete healing of the distal root, (e,f) and reduction in the lesion size of the mesial root.

Figure 4 Flowchart of the trial showing the process of patient recruitment, exclusion, and follow-up.

Figure 5 Frequency distribution of teeth according to tooth type.

Figure 6 Percentage of unfavourable outcomes associated with teeth presented with less or more than 30% of volume of remaining coronal tooth structure.

Table 1 The outcome categories for root canal retreatment (Patel *et al.* 2012b, Davies *et al.* 2016)

Score	Description	Outcome
1	New periapical radiolucency	Unfavourable outcome
2	Enlarged periapical radiolucency	Unfavourable outcome
3	Unchanged periapical radiolucency	Unfavourable outcome
4	Reduced periapical radiolucency	Favourable outcome
5	Resolved periapical radiolucency	Favourable outcome
6	Unchanged healthy periapical status (no radiolucency before and after retreatment)	Favourable outcome

Table 2 Reasons for patients’ non-attendance at the review appointments

Reasons for drop out	Number of patients
Withdrawal of consent	3
Loss of contact with patient	7
Patient passed away	2
Work commitments	3
Pregnancy at review time	1
Health issues	1
Relocation to another country	2
Total	19

Table 3 Frequency distribution of outcome of treatment for each tooth assessed using periapical radiographs (PA) and cone beam computed tomography (CBCT) (n=132)

Outcome category	Maxillary premolar		Maxillary molar		Mandibular premolar		Mandibular molar		% (all cases)	
	PA	CBCT	PA	CBCT	PA	CBCT	PA	CBCT	PA	CBCT
1- new lesion	0	0	0	0	0	0	0	0	0 (0)	0 (0)
2- enlarged lesion	0	1	3	4	0	0	1	4	3 (4)	6.8 (9)
3- unchanged lesion	1	2	3	3	0	0	2	6	4.5 (6)	8.3 (11)
4- reduced lesion	2	4	4	12	2	3	16	26	18.2 (24)	34.1 (45)
5- resolved lesion	6	10	9	15	1	1	32	22	36.4 (48)	36.4 (48)
6- no lesion before/after retreatment	12	4	24	9	3	2	11	4	37.9 (50)	14.4 (19)

Table 4 Percentage of favourable and unfavourable outcomes based on clinical symptoms and radiographic examination with periapical radiographs (PA) and CBCT (n=137)

Outcome category	Maxillary premolar		Maxillary molar		Mandibular premolar		Mandibular molar		All cases	
	PA	CBCT	PA	CBCT	PA	CBCT	PA	CBCT	PA	CBCT
Unfavourable (1,2,3)	9.1	18.2	19.6	21.7	0	0	7.9	17.5	11.7	18.2
Healing (4)	9.1	18.2	8.7	26.1	33.3	50	25.4	41.3	17.5	32.8
Healed (5,6)	81.8	63.6	71.7	52.2	66.7	50	66.7	41.3	70.8	48.9
Favourable (4,5,6)	90.9	81.8	80.4	78.3	100	100	92.1	82.5	88.3	81.8

Table 5 Kappa values for agreement between and within examiners on outcome diagnosis using periapical radiographs (PA) and CBCT, and on quality of coronal restorations

	PA	CBCT
Inter-examiner agreement for treatment outcome	0.72	0.71
Consensus agreement for treatment outcome	0.71	0.71
Consensus agreement for coronal restorations quality	0.76	-

Table 6 Frequencies and percentages of unfavourable outcomes among groups within different coronal walls remaining (teeth with pre-existing crowns were excluded) (n=89)

Remaining coronal walls	No of samples	No of unfavourable outcome	% Unfavourable outcome
One wall	3	0	0
Two walls	19	4	21.1%
Three walls	55	10	18.2%
Four walls	12	1	8.3%
Total	89	15	16.9%

Table 7 Quality of coronal restoration in relation to root canal retreatment outcome (n=132) (teeth which failed before the one-year recall were excluded)

Coronal restoration quality assessment	Score	No.	Total (%)	Retreatment outcome		
				Favourable	Unfavourable	% Unfavourable
Clinically	Acceptable	126	95.5	106	20	15.9
	Unacceptable	6	4.5	6	0	0
Radiographically	Acceptable	125	94.7	107	18	14.4
	Unacceptable	7	5.3	5	2	28.6
Combined (clinically and radiographically)	Acceptable	120	90.9	102	18	15
	Unacceptable	12	9.1	10	2	16.7